Charting a Course Toward Diagnostic Monitoring: A Continuing Review of Coral Reef Attributes and a Research Strategy for Creating Coral Reef Indexes of Biotic Integrity

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Abstract

This paper continues our review of coral reef attributes and presents a research strategy for creating coral reef indexes of biotic integrity (IBI's) that, once developed, can be used in coral reef biocriteria programs and for the diagnostic monitoring of coral reefs around the world. A framework for the definition of coral reef multimetric indexes is provided and we demonstrate how existing research fits into this framework. The research strategy has 6 components; sessile epibenthos, benthic macroinvertebrates, fish, macrophytes, phytoplankton and zooplankton. The research strategy is based on our best judgement, other expert opinion, and available information. It draws on techniques that have been successful in freshwater, estuarine, and temperate marine biocriteria programs and outlines those that will likely be successful in coral reef environments. Understanding the tolerance and intolerance of coral reef taxa to specific, as well as combinations, of chemical pollutants and other human influences will be crucial in creating effective IBI's. We emphasize that this research strategy is just a starting point. The attributes, their response specificity, and their predicted response must be specified by pilot program research. It is hoped that this strategy will stimulate research in the development of coral reef IBI's and produce new ideas and results that will move this important endeavor forward. Additional steps required include development of a coral reef classification system and selection and sampling of minimally disturbed sites to define reference condition or regional ecological expectations.

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Introduction

The purpose of this paper is to continue our review of coral reef attributes (Jameson et al. 1998) and to present a research strategy for creating coral reef indexes of biotic integrity (IBIs) (Karr and Chu, 1999). Once developed, IBIs can be used in coral reef biocriteria programs (Jameson et al. 1998) for diagnostic monitoring of coral reefs around the world. The following research strategy is based on our best judgement, other expert opinion, and available information. It draws on techniques that have been successful in freshwater, estuarine and temperate marine biocriteria programs and outlines those that will likely be successful in coral reef environments. We emphasize that this research strategy is just a starting point. The attributes, their response specificity, and their predicted response may require revision based upon results of pilot program research. It is hoped that this strategy will stimulate research in the development of coral reef IBIs and produce new ideas and results that will move this important endeavor forward. Table 1 provides definitions for key terms used in this paper.

Table 1. Key terms used in defining biological condition (adapted from Karr and Chu, 1999).

Term	Definition
Endpoint	A measured characteristic that indicates the condition of a biological, chemical or physical system
Attribute	Measurable part or process of a biological system
Metric	Attribute empirically shown to change in value along a gradient of human influence (i.e., a dose-response context is documented and confirmed)
Multimetric index	An index (expressed as a single numerical value) that integrates several biological metrics to indicate a site's condition (ex., an index of biotic integrity - IBI)
Biological monitoring	Sampling the biota of a place (i.e., coral reef)
Biological assessment	Using samples of living organisms to evaluate the condition of places

Biological integrity	The condition at sites able to support and maintain a balanced, integrated, and adaptive biological system having the full range of elements and processes expected for a region. Biological integrity is the product of ecological and evolutionary processes at a site in the relative absence of human influence (Karr 1996)
Biocriteria (biological criteria)	Criteria which define a desired biological condition for a water body and can be used to evaluate the biological integrity of the water body. When adopted by states, they become legally enforceable standards (narrative expressions or numerical values)
Designated aquatic life use	Descriptions of the optimal use of each waterbody as defined by states (i.e., natural, fisheries, recreational, transportation, or mixed use)

Where Are We?

Coral Reefs Are Losing Their Living Components

Coral reefs continue to deteriorate as a result of human society's actions; devastation is obvious, even to the untrained eye (Ginsburg, 1994; Jameson et al., 1995; Bryant et al., 1998; Hodgson, 1999). Human impacts decrease ecosystem resiliency to natural change. In 1997-1998 the global coral reef monitoring network and volunteer groups like Reef Check observed the most severe bleaching event in history (Wilkinson, 1998; Hodgson, 1999). They continue to monitor to see if these corals will recover or die and if damaged ecosystems will recuperate. Marine protected areas, such as Jamaica's Montego Bay Marine Park, are struggling to keep land-based sources of pollution from killing their reefs (Huber and Jameson, 1998; 1999; 2000; Jameson and Williams, 2000). From 1992 to 1997 they have seen coral-smothering algal cover increase dramatically and over-fishing has wiped-out critical grazing fish populations (Sullivan and Chiappone, 1994; Williams and Polunin, in press). Even regions with good water quality, like the Red Sea and Gulf of Aqaba, are fighting to keep anchor and fishing gear damage from physically pulverizing their valuable coral resources (Jameson, 1998; Jameson et al., 1999; Fadlallah, 1999).

Other less visible, but potentially more devastating threats include increased atmospheric carbon dioxide concentrations that could decrease oceanic pH and carbonate ion concentrations and result in reduced coral calcification rates (Kleypas et al., 1999). These oceanic chemical changes, combined with other stresses such as, elevated temperatures and bleaching, could kill corals on a global scale (Buddemeier, 1999). Further studies at the ecosystem level will help to verify this hypothesis.

Society Can Not Afford To Lose The Economic Benefits Of Coral Reefs

Coral reefs are some of the most diverse, valuable, and vulnerable marine habitats on the earth. They provide millions of people with food, tourism revenue, coastal protection and new medications for increasingly drug-resistant diseases — despite being among the least monitored and protected natural habitats in the world. Tens of thousands of species have been identified on coral reefs, and estimates suggest that coral reefs may be home to more than nine million species of plants and animals (Bryant et al., 1998). The magnitude of fish harvests per unit area from coralline shelves approximates those taken by trawlers from temperate shelves and it is estimated (conservatively) that the potential global annual harvest from tropical reef fisheries is 6 million metric tons (Munro, 1996). Over half of all managed fishery species in the United States spend important parts of their lives on or around coral reefs (USCRTF, 1999). Some of the most promising biotechnological innovations in the future may come from coral reef species. As much as 90% of the animal protein consumed on many Pacific Islands comes from marine sources (IUCN, 1993). Tourism, commercial, recreational, and subsistence fishing, and the protection of coastal communities and ports from storms, provide economic benefits estimated to be in excess of $375 billion per year worldwide (Costanza et al. 1997). In 1990 the coral reefs of Florida alone have been estimated to generate about $US1.6 billion from recreation uses (USDOC, 1994). In the Caribbean, tourism generates up to 30% of investment and GDP (Dixon et al., 1993; Hill 1998). In 1990, Caribbean tourism earned $US8.9 billion and employed over 350,000 people (Jameson et al., 1995). In Hawaii, coral reefs are central to a $US700 million and expanding marine recreation industry. Reef fish, lobsters, and bottom fish generate about $US20 million in landings annually and are an important source of food for local and restaurant consumption (Grigg, 1997). In Guam and the Northern Marianas, 90 percent of economic development is related to coastal tourism (NOAA, 1998). Between 1985 and 1995, visitor numbers on Guam rose from 300,000 to 1,300,000 per year and the hotel industry is now the single largest private sector employer on Guam. Diving brings $US148.6 million annually to Guam (Birkeland, 1997). Tourism to the Great Barrier Reef generates about $US1 billion (Done et al., 1996).

Diagnostic Biological Monitoring Is Essential To Manage Coral Reefs

Coral reef monitoring programs have become ubiquitous over the course of the past two decades (Risk, 1992; Eakin et al., 1997), ranging from monitoring by individual research scientists to that conducted by large institutions, also including regional networks such as the CARICOMP (Caribbean Coastal Marine Productivity) network (CARICOMP, 2000) and the Atlantic and Gulf Reef Assessment (AGRA) rapid assessment protocol (Steneck et al., 1997), and world-wide efforts such as the Global Coral Reef Monitoring Network (GCRMN, 2000). The scope of reef monitoring has recently expanded even further with the introduction of monitoring programs specifically designed for volunteer sport divers, such as the ReefBase Aquanaut, Reef Check and RECON programs (McManus et al., 1997; Reef Check, 2000; CMC, 2000). While these state of the art efforts have been very successful at what they were designed to do — document change in coral reefs — they have been for the most part, non-diagnostic; i.e., not capable of predicting what is causing the changes.

Because of the non-diagnostic nature of most coral reef monitoring programs, policy makers and government officials are not well equipped to communicate to the public or politicians trends in the condition of coral reef systems, the cause of coral reef resource decline, or the appropriate solution for remediation. To protect coral reef resources we should track the biological condition of these ecosystems the way we track local and national economies or diagnose personal health — using calibrated metrics — that integrate the influence of all forms of degradation caused by human actions and can thus help guide diagnostic, curative, restorative and preventive management actions.

Understanding Biological Attributes, Biological Condition, and Reference Condition Is Important In Diagnostic Monitoring

To build effective multimetric indexes it is critical to find the right attributes of a coral reef system to measure. Attributes that do not change in response to human impact tell nothing about the consequences of human activities for a particular coral reef location and its biota. Metrics must be selected based on whether they reflect specific and consistent biological responses to human activities. Ideal metrics should be relatively easy to measure and interpret. They should either increase or decrease predictably as human influence increases and should be sensitive to a range of biological stress (but in some cases can be response specific). Most important, metrics must be able to discriminate human-caused changes from natural variation (Karr and Chu, 1999).

Human activities degrade coral reefs by changing one or more of five principal groups of attributes (Table 2) often through undetected yet potentially devastating effects. Because properly-designed multimetric indexes are sensitive to these five factors, they quantify the biological effects of a broad array of human activities (Karr and Chu, 1999). The focus of a metric may be an indicator organism, many organisms, or in other cases it is not an organism at all, but some other biological attribute (i.e., nitrogen isotope ratios in macrophyte tissue).

The use of biological attributes has been justified in marine pollution monitoring programs focusing on chemical contamination for at least three reasons (Maher and Norris, 1990). First, they assess only those pollutants which are bioavailable, ostensibly those which are most important. Second, they can reveal biological effects at contaminant levels below current chemical analytical detection limits (either due to chronic, low level pollution or short-term pulses). Third, biological attributes can help assess synergistic or additive antagonistic relationships among pollutants, an important consideration with the typical combination of pollution impacts impinging on most reefs in the developing world (Ginsburg, 1994).

A far more important point and advantage of biological attributes is that they are useful in detecting human degradation caused by factors other than chemical contamination (Table 2).

The aim of any coral reef assessment program is to distinguish relevant biological signal from noise caused by natural spatial and temporal variation. Faced with the dizzying number of variables, disturbances, end-points, and processes, marine managers and researchers have periodically failed to choose those attributes that give the clearest signals of human impact. The world’s coral reefs have suffered as a result.

Table 2. Five attributes of coral reef resources altered by the cumulative effects of human activity (adapted from Karr and Chu, 1999), with examples of degradation from Montego Bay, Jamaica (Jameson and Williams, 2000).

Attribute	Components	Degradation in Montego Bay
Water quality	Temperature, turbidity, dissolved oxygen, salinity, organic and inorganic chemicals, heavy metals, toxic substances	Coral bleaching from increased temperature and bacteria. Fish kills from oxygen depletion. Algal blooms from increased nutrients. Coral mortality from sedimentation. Potential coral mortality from greenhouse gasses (CO_2 increases & pH changes).
Habitat structure	Substrate type, water depth and current speed, spatial and temporal complexity of physical habitat	Coral physical damage and mortality from anchors, divers, boats and fishing gear.
Flow regime	Water direction, volume, flow timing	Port construction with peninsula road causing flow changes, oxygen depletion, fish kills, coral mortality and changes in fish population dynamics.
Food (energy)	Type, amount and size of organic source particles entering reef, seasonal pattern of energy availability, light intensity	Light intensity reduced by sediment and sewage inputs.
Biotic interactions	Changes in competition and predation, stimulated by fishing, disease, parasitism, mutualism, and introduction of alien taxa	Sport and commercial fishing. Coral disease. Sea urchin die-off. Algal overgrowth of coral.

The biological condition of coral reef systems within a region is usually a continuum, varying from near pristine to severely degraded. To fully understand, rank, and evaluate those reefs, researchers should also measure biological condition on a continuous scale along this gradient (Ellis and Schneider 1997). Multimetric biological indexes furnish a yardstick for measuring, tracking, evaluating, and communicating continuous variation in biological condition. Instead of simply labeling a site "control" or "treatment", "impaired" or "unimpaired", "acceptable" or "unacceptable", a multimetric assessment identifies and preserves finer biological distinctions among sites, in the index itself and in the values of the component metrics. Dichotomous methods for evaluating biological condition lead to a variety of analytical and even regulatory problems. What is or is not an acceptable threshold in some biological (or chemical) metric depends on a site's context. Thresholds acceptable on a coral reef close to urban development may be totally unacceptable on a reef within a marine protected area. In addition, threshold definitions change over time as science and human values change, as people learn more, and as measurement techniques become more sophisticated.

Measuring biological condition with a continuous yardstick such as an IBI puts a site along a continuum of condition in comparison with other sites or other times, allowing thresholds to be reset according to context. It also permits a ranking of many sites — which might all be labeled "degraded" in a dichotomous scheme — so that priorities may be set for budget-constrained protection and restoration efforts.

Biological assessment must have a standard (reference condition) against which the conditions of one or more sites can be evaluated. In multimetric biological assessment, reference condition equates with biological integrity. IBIs measure the divergence from biological integrity. When divergence is detected, society has a choice: to accept divergence from integrity at that place and time, or to restore the site. There are few, if any, coral reefs remaining in the world that have not been influenced by human actions. Defining and selecting reference sites, and measuring conditions at those sites, requires a careful sampling and analysis plan.

A Continuing Review of Coral Reef Attributes

Jameson et al. (1998) review the status of biomonitoring using coral reef attributes. Appendix 1 includes new additions to this review. With few notable exceptions (Table 3), the majority of these attributes have not yet been fully developed into usable metrics (i.e., a metric for which a quantitative dose-response change in attribute value has been documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation). Metrics should also be calibrated for the specific locations for which they are intended to be used in and metric values transformed into scores. In these respects, coral reef diagnostic monitoring lags far behind freshwater and temperate marine programs, many of which use metrics that have undergone extensive calibration and have been developed into multimetric indices of biotic integrity with well-defined interpretative frameworks (e.g., Karr et al., 1986; Lenat, 1988; Lang et al., 1989; Karr,1991; Rosenberg and Resh, 1993; Kerans and Karr, 1994; Wilson and Jeffrey, 1994; Davis and Simon, 1995; Karr and Chu, 1999; Simon, 1996). Many of these indexes result in the calculation of a simple numerical “score” for a particular site, which can then be compared over time or with other sites. Such rankings have an intuitive appeal to resource managers and users, and can be an effective means of galvanizing political willpower towards pollution prevention and conservation activities. Because the multimetric index is grounded in biological context and situation it can be expressed as a single number (IBI) or the metrics within the IBI can be expressed in a narrative that describes exactly how the biota at a site differs from what might be expected at a minimally disturbed site. The potential for diagnostic uses to identify causes of degradation is present as well.